Rapid Prototyping Journal

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Abstract

Purpose – The purpose of this paper is to present the first detailed three-dimensional (3D) print from micro-computed tomography data of the skeleton of an ancient Egyptian falcon mummy.

Design/methodology/approach – Radiographic analysis of an ancient Egyptian falcon mummy housed at Iziko Museums of South Africa was performed using non-destructive x-ray micro-computed tomography. A 1:1 physical replica of its skeleton was printed in a polymer material (polyamide) using 3D printing technology.

Findings – The combination of high-resolution computed tomography scanning and rapid prototyping allowed us to create an accurate 1:1 model of a biological object hidden by wrappings. This model can be used to study skeletal features and morphology and also enhance exhibitions hosted within the museum.

Originality/value – This is the first replica of its kind made of an ancient Egyptian falcon mummy skeleton. The combination of computed tomography scanning and 3D printing has the potential to facilitate scientific research and stimulate public interest in Egyptology.

Keywords South Africa, Rapid manufacturing, 3D, Radiography, Bones, Prototyping

Paper type Case study

1. Introduction

Although the ancient Egyptians are renowned for their human mummies, their production of animal mummies is less well known despite the fact that they number in the millions (Ikram, 2005). The preservation of the body was important to the ancient Egyptians, as they believed that the soul needed a vehicle to continue its existence in the afterlife; the earthly body was regarded as ideal for this, although two- and three-dimensional (3D) images in the form of murals and statuettes were also provided for the deceased as insurance.

While the reasons for creating animal mummies are unclear, current archaeology divides animal mummies into five broad categories:

1 pets which accompanied their owners in life and followed them in death;
2 victual mummies served as food for the dead;
3 sacred mummies were an earthly incarnation of a god, for example, the Apis bull of Ptah (Dodson, 2005);
4 votive mummies, given as an offering to a specific god, are the largest category of animal mummies found in collections; and
5 "other", which do not fit into any of these categories and are currently under study (Ikram, 1995, 2005, 2012; Ikram and Iskander, 2002).

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Rapid Prototyping Journal
21/4 (2015) 368–372
© Emerald Group Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/RPJ-09-2013-0089]

Funding for the project was provided by Stellenbosch University Subcommittees A and B. The micro-CT scanner at Stellenbosch University's Central Analytical Facilities was acquired via the South African National Research Foundation equipment fund. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript. The authors thank Stellenbosch University and Central University of Technology for providing facilities. The kind cooperation of Iziko Museums of South Africa is acknowledged. Megan Spitzer from the Division of Birds, Smithsonian Institution, Washington, DC, kindly verified the identification of the falcon. Carina Beyer and Eva Raal took the photographs of the falcon mummy and 3D print, respectively.

Received 8 September 2013
Revised 12 January 2014
12 February 2014
Accepted 25 February 2014

Rapid Prototyping Journal
Volume 21 · Number 4 · 2015 · 368–372

Animal mummies have been studied sporadically for a few centuries (Pettigrew, 1834; Gillispie and Dewachter, 1987; Ikram, 2012; Ikram, 2015). Attention was paid to them as a manifestation of Egyptian funerary beliefs and embalming technology, as well as a source of information concerning the fauna of ancient Egypt. More recently, they have also been studied to learn about disease and veterinary care, breeding programmes and the ancient Egyptian environment (Ikram and Iskander, 2002; Ikram, 2005, 2012; Ikram, 2015). Mummies have been studied macroscopically, but are now increasingly examined through radiography. This non-invasive technique allows one to identify the animal found inside the wrappings, how it was killed, diseases it may have had and the mode of mummification, all without violating the integrity of the object (cf. Ikram and Iskander, 2002; Ikram, 2005; McKnight, 2010; Bailleul-LeSeur, 2012; Cornelius *et al.*, 2012; Ikram, 2015).

Radiographical analyses of mummies using x-rays have been undertaken since 1898 (Harwood-Nash, 1979). Since 1979, a more advanced method, computed tomography (CT) scanning, has been successfully used to analyse and study wrapped ancient Egyptian human mummies (Harwood-Nash, 1979; Notman *et al.*, 1986; Baldock *et al.*, 1994; Hoffman *et al.*, 2002; Lynnerup, 2010; Bailleul-LeSeur, 2012; Cornelius *et al.*, 2012). These studies generally make use of medical full-body CT scanners, which generate volumes of information about the inside of the objects at resolutions of down to 500 μm. Most CT scans of Egyptian mummified objects are carried out with medical CT scanners because of their widespread availability, as well as the size of human and animal mummies, which match the available scannable volume of medical scanners. The use of CT scanning for the analysis of mummies has even become a gold-standard method (Rühli *et al.*, 2004; Chhem, 2006). A number of animal mummies have also been analysed using CT scanning, including (among others) birds of prey, cats and ibises (Falke *et al.*, 1987; Ikram, 1995; Jackowski *et al.*, 2008; Morgan and McGovern-Huffman, 2008; McKnight, 2010; McKnight *et al.*, 2011; Morgan *et al.*, 2011; Bailleul-LeSeur, 2012; Cornelius *et al.*, 2012; Gnudi *et al.*, 2012; Wade *et al.*, 2012).

Additive manufacturing technology (Chua *et al.*, 2010) has advanced to the point where today 3D prints have been made of many archaeological objects, especially the hominid skulls (D'Urso *et al.*, 2000; Zhang *et al.*, 2000; Tobias, 2001; Pérès *et al.*, 2004; Fantini *et al.*, 2008; Kubo *et al.*, 2011), but also the heads of wrapped mummies (Cesarani *et al.*, 2004; Bens, 2010), and even a full-body replica of Tutankhamen (Materialise, 2013). All of these have been made at scan or print resolutions limited by medical-type scanners or by printers of limited resolution. Recent studies have combined the power of micro-CT technology with high-resolution 3D printing where Laycock *et al.* (2012) and Soe *et al.* (2012) generated a replica of a ninteenth-century Cantonese chess piece and a reconstruction of a medieval ship, respectively.

In this paper, we present the first such detailed print from micro-CT data of the skeleton of an ancient Egyptian falcon mummy. This can be used for museum display by placing the replica next to the wrapped specimen, and can also assist in physical analysis for the study of such an object.

2. Materials and methods

2.1 Ethics statement

All necessary permissions were obtained from the relevant authorities at the Social History Collections, Iziko Museums of South Africa, Cape Town, South Africa, to conduct this study. No permits were required in terms of the South African National Heritage Resources Act of 1999 (Act No. 25 of 1999) because no destructive methodology was applied in the described study. Object description and provenance is given in Table I.

2.2 Object and CT-scanning

Micro-CT scans of a wrapped animal mummy, a falcon, object SACHM 2575 (Figure 1), housed at Iziko Museums of South Africa, Cape Town, South Africa, were conducted between July 2012 and January 2013. The mummy is wrapped in several layers of coarse bandaging; it was created by desiccation through natron and the liberal application of resins, possibly mixed with oil and/or beeswax. Its provenance is unknown, although it might come from near the city of Akhmim, from where several other similar-looking mummies originate (Ikram and Iskander, 2002).

A commercial micro-CT scanner system, a phoenix v|tome|x L 240 (General Electric) with NF180 additional tube, was used. Radiographs were generated at 160 kV and 200 μA with 500 ms acquisition time per projection image with no averaging or skipping of images. A total of 3,000 images were recorded during one full rotation, making the

Table I Museum information on object SACHM 2575

Geographic location	Cape Town, South Africa
Museum	Iziko Museums of South Africa
Collection	Social History Collections
Museum accession number	SACHM 2575
Original museum catalogue description	Mummy hawk, Egypt S Cavanagh/Kavanagh, 1911
Display status	Slave Lodge, Iziko Museums of South Africa

Note: SACHM = South African Cultural History Museum

Figure 1 Photographs of the outer surfaces of the mummified falcon SACHM 2575

Source: Photographs Carina Beyer

total scan time approximately 35 minutes. A background detector calibration was carried out using a dark background, as well as two current settings (two-point calibration). A shift option was activated to shift the detector between projection images to minimize the rotation axis artefact sometimes visible in CT scans. A background region of interest was recorded for each image to normalize the background intensity during the scan. These projection images were then reconstructed using the system-supplied Datos reconstruction software, using 16-bit data type, with algorithms for minimizing beam hardening artefacts and correcting for movement of the sample or backlash of the rotation stage. The reconstructed volume was analysed in VGStudio MAX 2.1 (Volume Graphics). The geometrical resolution was set to 100 μm voxel size.

A surface fit was applied to the data, and the surface extraction tool of VGStudio MAX 2.1 was used (specifically, the "Normal with Simplification" option). This generates an STL file, readable by CAD programs. The STL file was imported into Magics (Materialise, Belgium) and separated into shells to separate the surface data from the background noise. The surface data were isolated and a "Shrink Wrap" feature was used to create a solid model from the surface data. Loose skeletal features were connected manually by creating small cylinders in between the loose features. The processed STL file was printed on a commercial 3D printing machine from Electro Optical Systems (GmbH) in PA2200 white polyamide at a resolution of 150 μm.

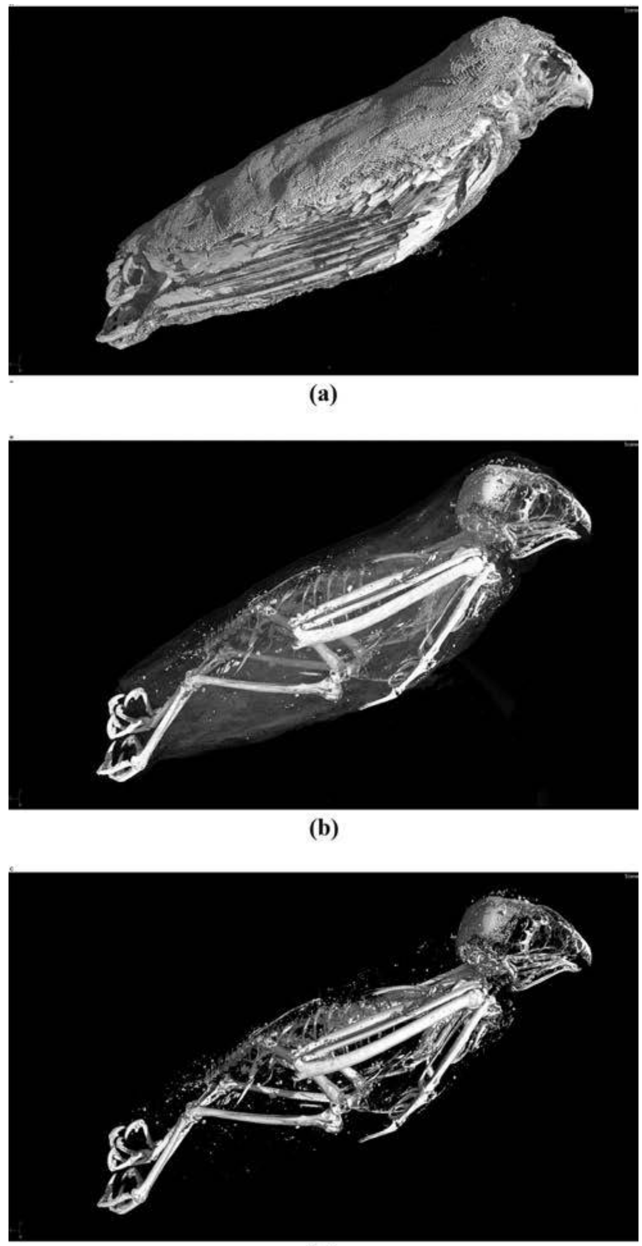
3. Results

The total time for completing the CT set-up, scanning, volume reconstruction and surface extraction was approximately 2 hours. The costs, including labour and instrument and analysis time, totalled US$140. The CT images taken were of such a quality that the lower-density materials were eliminated to reveal the surface of the whole skeleton [Figure 2(a)], orientation of the skeleton within the wrappings [Figure 2(b)] and the skeleton on its own [Figure 2(c)]. This allowed for the creation of a 3D polyamide representation on a 1:1 scale of the skeleton of the mummified bird (Figure 3). The approximate time it took for completing the model was 5.5 hours which included 1 hour of data manipulation and simplification and 4.5 hours of printing. The total cost for a single 1:1 scale print was US$280.

4. Discussion

Here, we reported on the creation of the first physical 3D reconstruction of the skeleton of an ancient Egyptian falcon mummy by combining data generated by CT scanning and advanced additive manufacturing. The data generated by the CT scanner was of sufficiently high resolution to create a high-quality reconstruction of SACHM 2575. Data generated by CT scanning allow for the non-destructive analysis of such animal mummies and minimizes handling of these valuable objects. By combining CT scanning and additive manufacturing technologies, it becomes possible to recreate the objects hidden by the wrappings of an animal mummy. Such reconstructions can be used for comparative morphological studies and measuring skeletal features, provided that the scale is 1:1, which can be applied to identify

Figure 2 Different views of rendered micro-CT scan data of SACHM 2575



(a) (b) (c)

Notes: (a) The surface of the wrappings; (b) the orientation of the skeleton within the wrappings; (c) the wrappings removed entirely, leaving only the skeleton

the species that was mummified. In this case, the identification was of a common kestrel (*Falco tinnunculus*; Slabbert *et al.*, manuscript in preparation), a bird frequently mummified in Egypt and, as with other raptors, associated with the sun god Re (Houlihan and Goodman, 1986; Ikram and Iskander, 2002).

Reconstructions using enlarged scales could also provide additional anatomical or visual information for researchers. The reconstruction of ancient objects also has an important

Figure 3 The 3D replica printed from the micro-CT data

Source: Photograph Eva Raal

role to play in public education and enhancing museum exhibitions. In this case, the model can be displayed in tandem with the actual mummy of the bird and give the viewer a better understanding of what is inside a mummy bundle. The museum visitor can even handle and study such a reconstruction themselves and not damage the original artefact. The combination of CT scanning and 3D printing is an exciting approach to reconstruct and display ancient animal mummies, and has a lot of potential for facilitating scientific research and stimulating interest in scientific Egyptology among the general public.

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